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PROVISIONAL APPLICATION COVER SHEET

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Signed: Richard E. Backus

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60/569659
050604

TITLE OF THE INVENTION (280 characters max)

SINGLE CRYSTAL SHAPE MEMORY ALLOY DEVICES

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[X] Drawings *Number of Sheets* 7 — [ ] Other *(specify)*:

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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

[X] Yes, the name of the U.S. Government Agency and the Government contract number are: US Navy SPAWAR #N39-03-C-0080

Respectfully submitted,

SIGNATURE: Richard E. Backus — Date 5/6/2004

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SINGLE CRYSTAL SHAPE MEMORY ALLOY DEVICES

Background of the Invention

1. Field of the Invention

This invention relates to devices and apparatus having a component in which large distortions can be advantageous.

2. Description of the Related Art

Shape memory alloy materials (also termed SMA) are well known. One common SMA material is TiNi (also know as nitinol), which is an alloy of nearly equal atomic weights of the elements Ti and Ni. An SMA material that has been annealed into a crystalline state undergoes a crystalline phase transformation from martensite to austenite when heated through the material's crystalline phase change transformation temperature. When below that temperature the material can be plastically deformed from a "memory shape" responsive to stress. When the SMA material is heated through the transformation temperature, it forcefully reverts to its memory shape while exerting considerable force.

In the prior art many different useful devices employing SMA have been developed and commercialized. The SMA used in the prior art devices are of polycrystalline form. Polycrystalline SMA exhibits both: 1) shape memory recovery (when cycled through the material's transformation temperature) and 2) superelasticity. Superelasticity is the property of the SMA material, when above the transformation temperature, having a strain recovery in the range of 3 to 4%. This is in comparison to a strain recovery on the order of only about 0.5% for non-SMA metals and metal alloys.

Shape memory alloys grown into a single crystal have been experimentally made in laboratories. Those single crystal shape memory alloys, when above the phase change transition temperature, exhibit a strain recovery on the order of about 9%. Because such 9% strain recovery is so far beyond the maximum strain recovery of

both convention polycrystal SMA materials and non-SMA metals and alloys, the strain recovery property of single crystal SMA will be referred to herein as "hyperelastic."

Objects And Summary of the Invention

It is a general object of this invention to provide a new and improved devices and apparatus having a component or components in which large distortions can be advantageous.

The invention in summary provides devices and apparatus having at least one component made of a single crystal shape memory alloy which exhibits hyperelastic properties that enable the component to undergo distortions that are much larger than could be obtained if the component were made of polycrystal SMA materials or non-SMA metals and alloys Such devices and apparatus include those that can serve as actuators for the active deployment of structures such as booms, antennae and solar panels; actuators for releasing door locks, moving mirrors and fuel injectors; flexures; constant force springs; connectors; dampeners; valves; microchip substrates; support members; non-explosive bolts; catheter guide wires; laproscopic instruments; medical implants such as stents; micro-connectors; switches; circuit breakers; electronic test equipment; consumer products such as safety valves, eyeglass frames and cellular phone antennae; and many other devices and apparatus in which large distortions of a component or components can be advantageous.

Brief Description of the Drawings

Fig. 1 is a chart comparing the superelastic property of a polycrystalline SMA with the hyperelastic property of a single crystal SMA.

Fig. 2 comprises one photograph showing on the left an unstrained rod of polycrystal SMA, and on the right the same rod strained with a 9% distortion.

Fig. 3 is a diagram showing apparatus for growing polycrystal SMA.

Fig. 4A is a cross-sectional view of an actuator in accordance with one embodiment shown in one operating position.

Fig. 4B is a cross-sectional view of the actuator of Fig. 4A shown in another operating position.

Fig. 5A is a side view of a heat pipe in accordance with another embodiment shown in one operating position.

Fig. 5B is a side view of the heat pipe of Fig. 5A shown in another operating position.

Fig. 6A is a side view of a switch flexure in accordance with another embodiment shown in one operating position.

Fig. 6B is a side view of the flexure of Fig. 6A shown in another operating position.

Fig. 7B comprises three perspective views of a boom flexure showing three different operating positions in accordance with another embodiment.

Fig. 8A is a perspective view of a leaf spring in accordance with another embodiment shown in one operating position.

Fig. 8B is a perspective view of the leaf spring of Fig. 8A shown in another operating position.

Fig. 9A is a perspective view of a collapsible tube in accordance with another embodiment shown in one operating position.

Fig. 9B is a perspective view of the collapsible tube of Fig. 9A shown in another operating position.

Fig. 10A is a cross-sectional view of a coil spring in accordance with another embodiment shown in one operating position.

Fig. 10B is a cross-sectional view of the coil spring of Fig. 10A shown in another operating position.

Fig. 11A is a perspective view of a device useful as a probe or pin in accordance with another embodiment shown in one operating position.

Fig. 11B is a perspective view of the device of Fig. 11A shown in another operating position.

Section 1: Identification and Significance of Phase I Work:

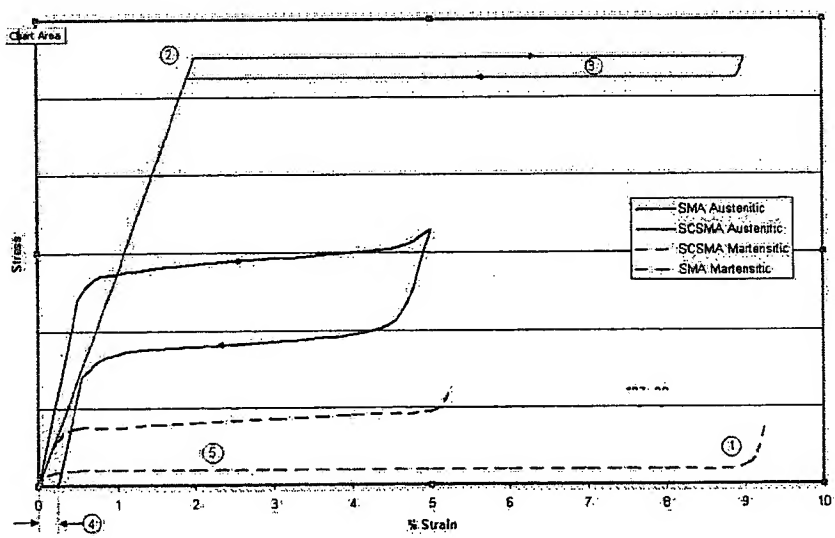
The Phase I effort was successful in yielding the following key objectives.

1) Design and manufacture of a custom crystal growing furnace capable of growing Single Crystal Shape Memory Alloy (SCSMA) made from Copper Aluminum and Nickel (CuAlNi). The purchase of this piece of equipment was funded by TiNi Aerospace at a cost of over $ 100,000.

2) Manufacture of "proof of concept" samples of SCSMA exhibiting significantly improved shape memory and superelastic properties as shown in figure 1 below.

By continuing with the phase II development as proposed herein, TiNi Aerospace has the opportunity to introduce a wide variety of SMA actuators and superelastic elements which will offer a significant advantage over devices currently available. For example, aerospace applications include actuators which may be used as motors to gently deploy spacecraft components such as booms, antennae and solar panels. Other aerospace applications include usage as constant force springs, flexures, or connectors which need to accommodate very severe deformations but spring back once the restraint is removed. Commercial applications are similarly wide scoped as the SCSMA may be introduced as a significantly improved replacement over existing SMA devices. These include actuators used in thermostatic valves, superelastic tools and instruments used by the medical industry, and other more familiar applications such as eye glass frames and cellular phone antennae.

The benefits of SCSMA technology over commercially available SMA are many and can be best demonstrated graphically through a comparison of their stress strain profiles as shown below.



Prior Art

Figure 1: Comparative of SCSMA material made from CuAlNi vs. commercially available SMA made from TiNi. See text below for description of benefit areas by number circled.

The improvements of SCSMA over SMA, as shown in figure 1, are described below:

1. 9% Strain Recovery. This represents a 3X gain in performance over SMA materials made from bulk TiNi. Note that depending on how the sample is used, the 9% recovery can either be used in the high temperature state as super-elastic spring, or deformed 9% when martensitic and heated to recovery as an actuator.
2. True constant force deflection: Unlike polycrystalline materials which reach their plateau strength in a gradual fashion and maintain an upward slope when deformed further, single crystalline materials have a very sharp and clear plateau force/stress and posses a truly flat spring rate when deformed up to 9%.
3. Very narrow loading hysteresis: This results in the same constant force spring rate during both loading and unloading. A characteristic which is key in superelastic applications where the flexure undergoes repeated cycling.
4. Recovery which is 100% repeatable and complete: One of the draw backs of polycrystalline SMA materials have always been the "settling" which occurs as the material is cycled back and forth. This has required that the material be either "trained" as part of the manufacturing process, or designed into the application such that the permanent deformation which occurs over the first "x" cycles does not adversely effect the function of the device. By comparison, SCSMAs do not develop such permanent deformations and therefore significantly simplify the design process into various applications.
5. Very low yield strength when martensitic: This is key in being able to design an SMA actuator which is 2 way (i.e. cycles back and forth between 2 states). This is typically done by incorporating a biasing element which overcomes the SMA when cold or martensitic and establishes position 1 until the SMA is heated and overcomes the biasing element and drives the mechanism to position 2. The problem with this type of device when using polycrystalline SMA is that the biasing element robs a significant amount of work output from the SMA. By comparison an equivalent SCSMA element will have a much lower yield strength when martensitic, requiring a much softer biasing element, and therefore generating a much greater net work output.
6. Ultra-low transition temperature: This characteristic is not possible to show graphically in figure 1, however, SCSMAs made from CuAlNi can be manufactured with a transition temperatures close to absolute 0 (i.e. –270 Celsius). This compares to SMA material made from TiNi which have a practical limit of ~ -100 Celsius. The advantage here is that the SCSMA may be used in various cryogenic applications such as those aboard spacecrafts which require cooling of certain instruments and sensors to very cold temperatures. In this case an SCSMA actuator may be used as a valve to control the flow of the cooling medium.

Figure 2 below shows a sample of SCSMA produced at TiNi Aerospace which although not yet fully characterized, demonstrates many of the above characteristics.

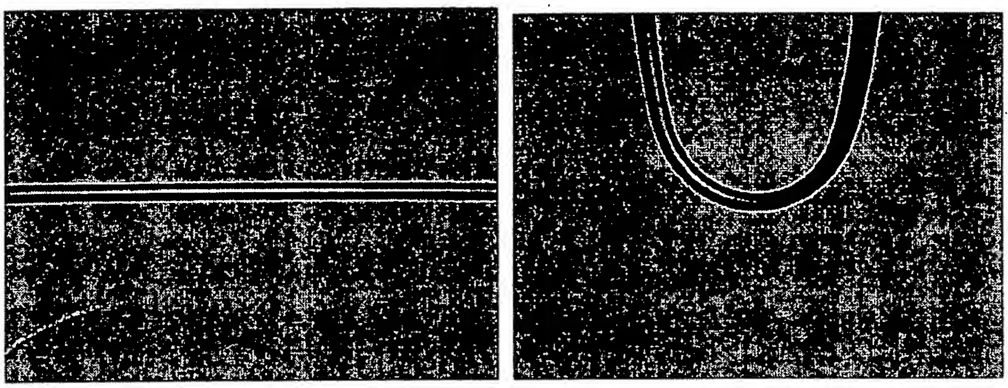


Figure 2: Sample of SCSMA produced at TiNi Aerospace which demonstrates 9% super-elasticity and/or shape recovery. Such a sample was delivered to the Navy Phase I TPOC (Technical Point of Contact) as proof of concept.

1.1 Manufacture of the Crystal Growing Machine (CGM)

The CGM was conceptually designed by TiNi Aerospace and manufactured by Watring Technologies (Huntsville Alabama) over the first 4 months of the Phase I effort. The design cycle went from conceptual illustrations of the CGM, to components drawings, and ultimately to the finished device. This is shown in figures 3A, 3B respectively.

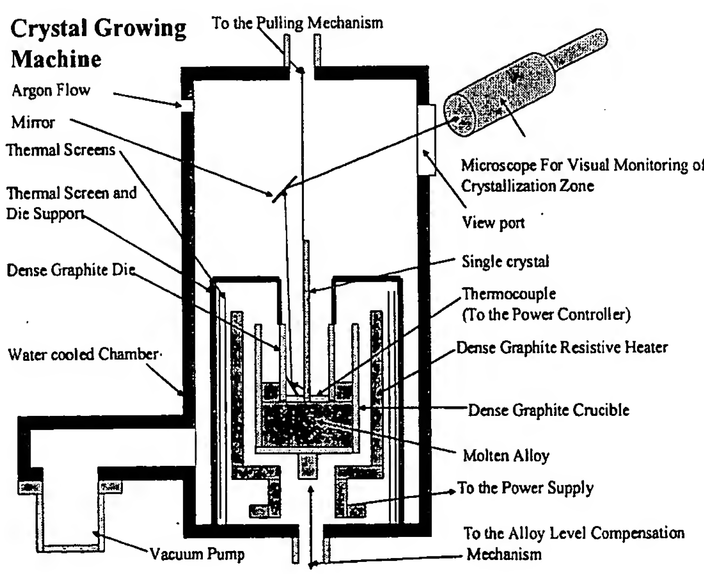


Figure 3A: Conceptual illustration of the CGM using the "Stepanov Method" as designed by TiNi Aerospace.

2.2 Technical Background:

Within the past two decades shape memory alloys (SMAs) have become popular for use as actuators due to their ability to generate substantial stress during shape recovery of large strains during temperature-induced phase transformations.[1] The energy density of such actuators is high compared to other alternatives: electromagnetic, electrostatic, bimetals, piezoelectric, and linear and volume thermal expansion effects of ordinary materials. The operation cycle of an SMA actuator includes deformation during or after cooling, and subsequent heating which results in a temperature-induced phase transformation and recovery of the deformation. SMA actuation is favored where relatively large force and small displacements are required in a device which is small in size and low in mass.

Shape memory is the ability of certain alloys to recover plastic deformation, which is based on a diffusionless solid-solid lattice distortive structural phase transition. The performance of shape memory alloy based actuators strongly depends on the amount of recoverable deformation. In turn, recoverable deformation itself is a function of the lattice distortion which takes place during martensitic phase transformation in the particular SMA. For an individual grain (single crystal) of SMA, the amount of possible recoverable strain after uniaxial loading, depends on the particular crystallographic orientation of the deformation tensor relative to the crystallographic axes of the high temperature (austenite) phase and the sign of applied load (tension or compression).

For a given deformation mode, the recoverable strain is strongly orientation dependent, and for the various crystallographic directions it differs by approximately a factor of two [2] . The restrictions imposed on a polycrystalline body by the deformation mechanism is another reason for diminished recoverable deformation in polycrystals as compared with a single crystal. To maintain integrity of the polycrystal, deformation of each particular grain has to be less than that corresponding to theoretical limit for lattice distortion.

<u>Therefore, for polycrystalline material, resultant recovery is the sum of particular grain deformations over the whole range of grain orientations, and is significantly smaller than the maximum value for an individual single crystalline grain.</u>[3]

<u>By comparison, recoverable deformation close to the theoretical value (lattice distortion) can be achieved in single crystalline SMA. In addition to the substantially increased recoverable deformation, absence of grain boundaries results in increased strength and longer fatigue life</u>. Specifically, as a single crystal, the strength of the grain for CuAlNi SMA can be as high as 800 MPa with the potential limit for recoverable deformation up to 9% and even higher for special deformation modes. An additional advantage of a single crystal SMA is that not only the thermally induced phase transformation may

contribute to the recoverable deformation, as in the case for polycrystals, but also the stress-induced martensite-to-martensite phase transitions. Depending on the material, this additional contribution may be up to 10%, therefore, the total theoretical recovery can be as high as 20%.

Since single crystals cannot be processed by any hot or cold mechanical formation without breaking single crystallinity, a special procedure is required for shaping single crystals in the process of their growth. The Stepanov method was developed for shaping a single crystal in the process of growth as the crystal is drawn from melt, resulting in a finished shape.[4]

<u>The objective of the proposed project is to develop a practical process for making SCSMA made from CuAlNi and to manufacture devices targeted at specific applications.</u>

2.3.1 Technical References and Footnotes:

[1] Shape Memory Materials, edited by K.Otsuka and C.M. Wayman, Cambridge University Press 1998, ISBN 0 521 44487 X (hc)

[2] The recoverable deformation of these polycrystalline SMA alloys, due to the lattice distortion during diffusionless solid-solid phase transition, is substantially lower than is theoretically possible for a given material. The main reason for this is that for a conglomerate of randomly oriented grains (as is normally the case for polycrystalline materials), the average deformation will always be less than the maximum available value for an individual grain. (The diffusionless nature of phase transitions in SMA results in strict lattice correspondence between the high temperature (austenite), and low temperature (martensite) lattices. As the symmetry of the martensite lattice is lower than that of austenite, maximum deformation in each grain can only be attained in one particular crystallographic direction. This means that for randomly oriented grains (as normally is the case for polycrystalline materials), the average deformation will be at least a factor of two less than maximum.)

[3] Shape Memory Alloys, H. Funakubo editor, Gordon and Breach Science Publishers, New York 1990.

[4] Single crystal growth and the Stepanov method are described in these papers:

Antonov P.I., Nikanorov S.P., Tatarchenko Y.A. The growth of controlled profile crystals by Stepanov's method, - J. Cryst. Growth, 1977, v.42, p. 447-452.

Schwuttke G.H., Yang K., Ciczek T.F. Electrical and structural characterization of silicon ribbons produced through capillary action shaping. - J. Cryst. Growth, 1978, v.43, p. 329-335.

Antonov P.I., Kosilov A.T., Vasilenko A.V. Properies of Cu-Al-Ni crystals grown by controlled profile Stepanov's method. -Proc. Academy of Science USSR, 1980, v. 44, p. 404-408. (in Russian)

G. H. Schwuttke, Low cost silicon for solar energy application. Phys. Stat. Sol. (a), 1977, vol3, N 1, p.43-51.

R.V. D'Aiello E.R. Levin, H. Kressel a. o. Epitaxial silicon solar cells on ribbon substrates. J. Cryst. Growth, 1977, vol. 39, N 1, P. 23-44

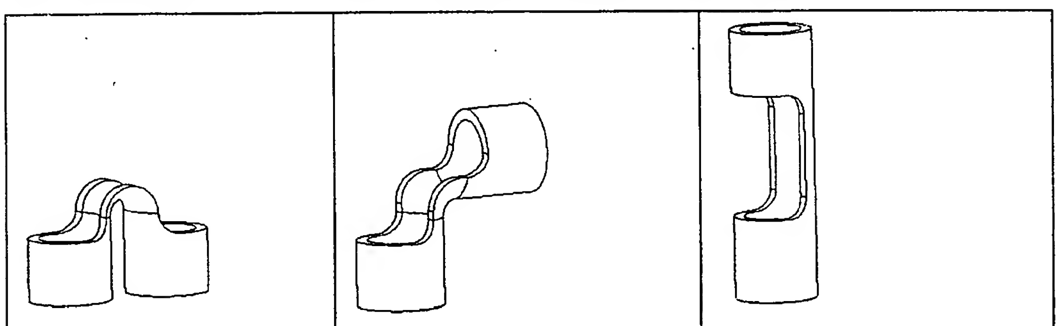
G.H. Schwuttke, K. Yang, T. Ciszek, Electrical and structural characterization of silicon ribbons produced through capillary action shaping, J. Cryst. Growth, 1978, V. 43, N 3, P. 329-335.

Task #9: 2nd Process Verification:

In order to determine the true applications possibilities of SCSMA it will be necessary to determine what secondary manufacturing processes can be performed on this unique material. For example, it has already been shown that exposure to high temperature and or stress can lead to recrystalization and the formation of unwanted crystals. The manufacturing processes which will be explored include Machining, EDM or Electro Discharge Machining, Grinding, Laser cutting, Electro-Polishing, and many others. These techniques will be used to manufacture a host of basic shapes including the following:

Rods	Ribbons	Flexures
Coil Springs	Leaf Springs	Serrated Tubes
Tubes	Pins	Bi-Stable Elements

Of particular interest are flexures of the type shown in figures 7A This type of device offers additional stiffness when in the extended position and has been manufactured from traditional materials such as Stainless Steel or Beryllium Copper. However, their usage aboard space applications has been limited to smaller deployables primarily because they lack the stiffness necessary to support larger structures. This is due to the very limited strain (< 0.3% elastic) which these materials can endure and therefore to achieve the necessary 180 degree fold for compact stowage, they must be made ultra thin reducing their axial stiffness. By comparison, the 9% strain recovery capability of SCSMA samples allows flexures like these to be made in the order of 30 times thicker providing an order of magnitude increase in axial rigidity.



Stowed Position | Partially Deployed | Fully Deployed

Figure 7A: Flexures which when made from SCSMA material may be integrated into various boom designs such that the resulting structure is both stiffer and able to be stowed more compactly.

Section 6: Potential Post Research and Development Applications:

The potential for this technology is truly enormous by all accounts. The following table illustrates just some of the applications for this technology.

Industry	Application Area
Aerospace Military	• As an Actuator used for active deployment of a host of devices including booms, antennae, or solar panels. • As a flexure or constant force spring used for passive movement of cover doors or hinges. • As a connector where it is necessary to accommodate significant motion of adjacent parts. For example, heat pipes aboard spacecraft require such connectors to carry heating/cooling capability across a hinge line to a deployable. • As a dampener used to absorb or mitigate energy coming from nearby pyrotechnic release devices. • As a valve for a broad range of temperatures including cryogenic. Such valves have applications aboard missiles and satellites that carry sophisticated instruments such as sensors or cameras that need to be cryogenically cooled. • As an actuator in arming and safing of ordnance • As a substrate or support member for a surface or component which needs to accommodate large motion. TiNi is aware of applications on optical assemblies which require both support and actuation (movement). • As an improvement to TiNi Aerospace's own line of SMA based products. In particular this technology may enable the fabrication of a much smaller Frangibolt^R Actuator.
Medical	• For making catheter guide wires which are significantly more flexibe than those currently made from stainless steel or SMA. • In laproscopic instruments where it is increasingly necessary to make tools which can tolerate large distortion. • Also may be used in implants such as stents if the material can be made bio compatible by coating with Au.
Automotive	• SMA have been suggested as actuators for releasing door locks, moving mirrors, and even for driving fuel injector valves.
Computer	• In micro-connectors and switches where large displacement capability allows for more reliable assembly and or the fabrication of smaller parts.
Commercial	• Rings made of SMAs have been used as metallic connectors to

	secure braid in cabling applications. • Used in switches, relays, circuit breakers, and electronic test equipment
Consumer Products	• Anywhere SMAs are currently being used such as in safety valves, eyeglass frames, and cellular phone antennae.

Actuator

Fig 4A

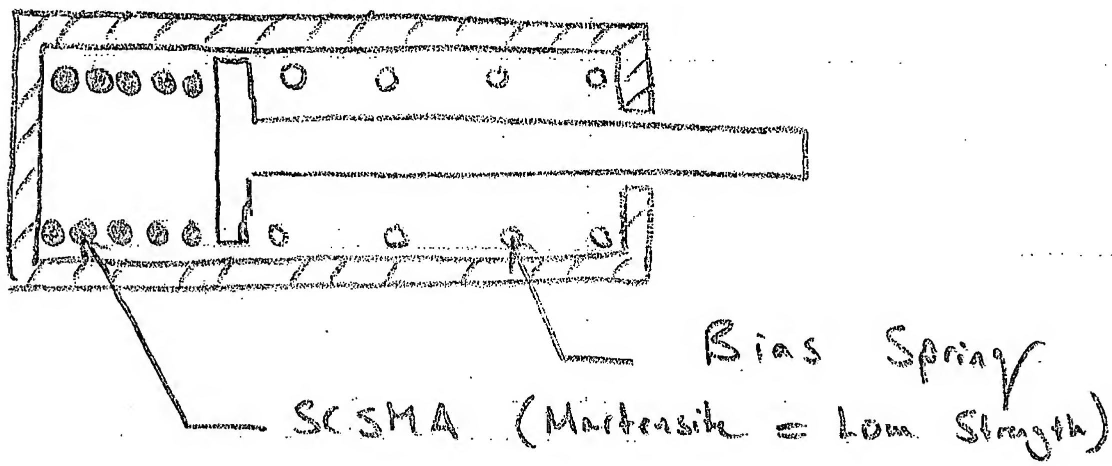
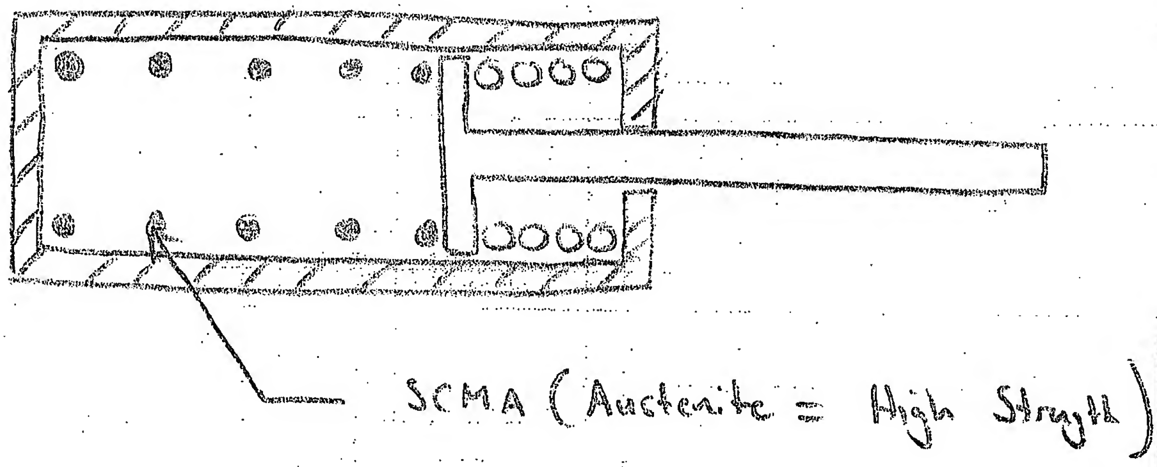


Fig 4B



Use of SCSMA allows the strength of the Bias Spring to be minimized therefore maximizing the Net work output of the Actuator. This type of mechanism can take numerous shapes.

5/4/04

Heat Pipe

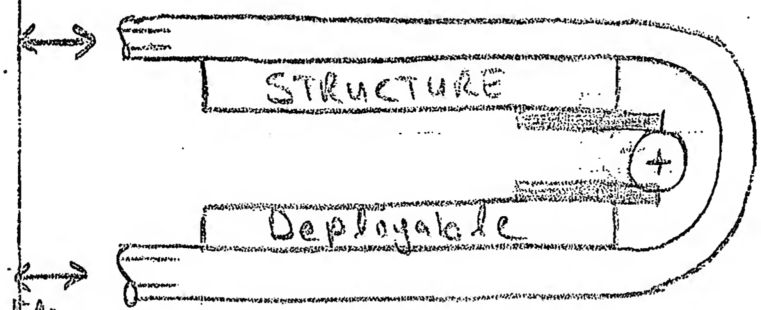


Fig 5A

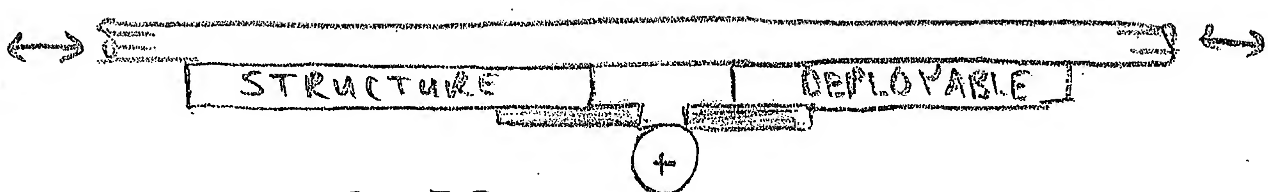


Fig 5B

Use of SCSMA allows tubes to be manufactured which can tolerate severe bending, as is needed in Heat Pipes aboard satellites which traverse a hinge line.

5/4/04

Flexure for Switch

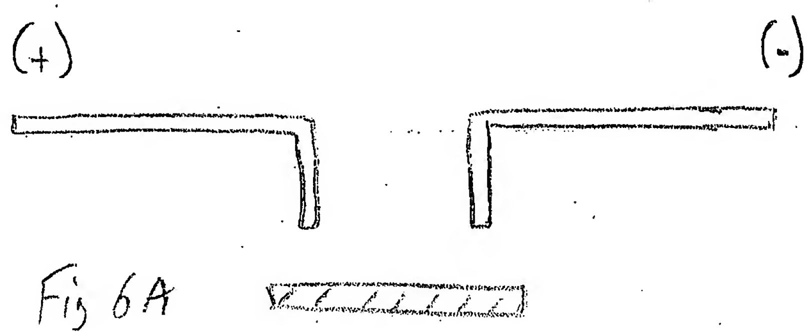


Fig 6A

(Open)

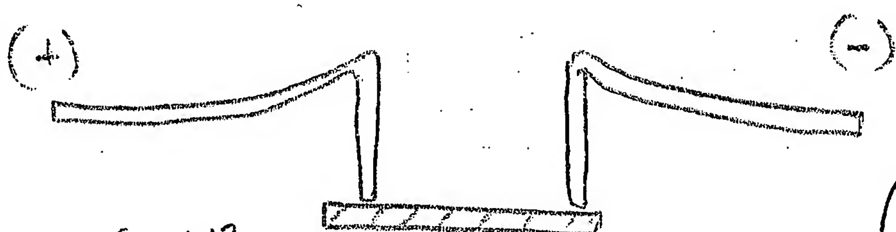


Fig 6B

(Closed)

Use of SCSMA allows for manufacture of components which are smaller and more forgiving (reliable) to manufacturing tolerances.

[signature] 5/4/04

Leaf Spring

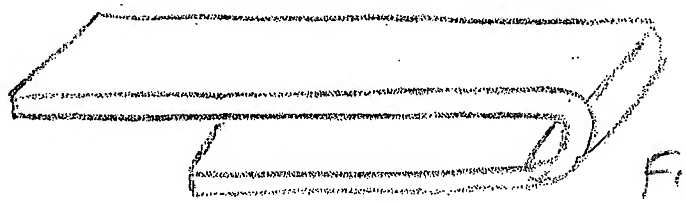


Fig 8A

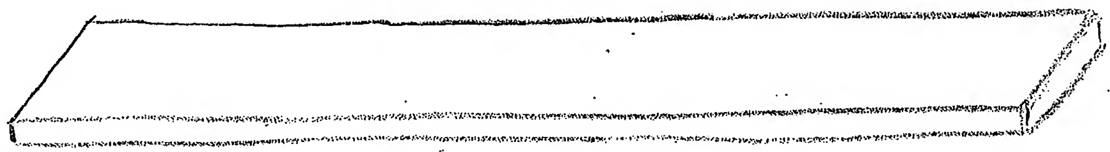


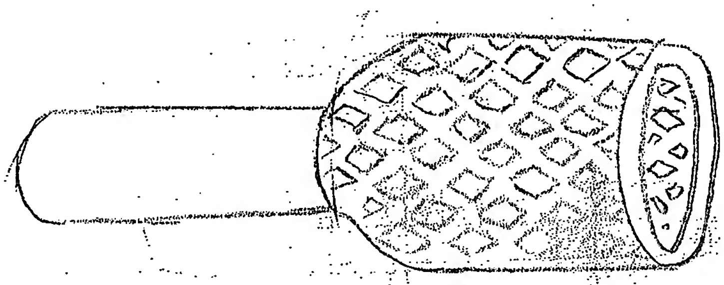
Fig 8B

Use of SCSMA allows for extreme bending, particularly useful in Aerospace applications where size and mass must be minimized.

The constant force plateau stress also offers a significant advantage in giving the element an inherent "locking" feature as well as minimizing the total energy stored when fully bent (strained to 9%)

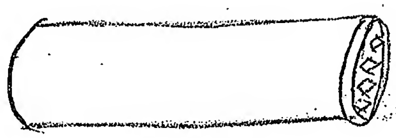
5/4/04

Collapsible Tubes



Partially Deployed

Fig 9A



Retained in much smaller tube

Fig 9B

The SCSMA allows tubes to be collapsed much further than normal materials or SMAs. Application includes stents.

5/4/04

Coil Spring

Torsion, Tension, or Compression (as shown)

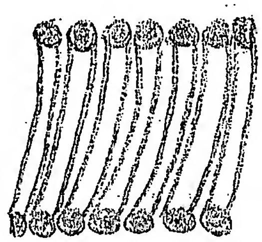


Fig 10A

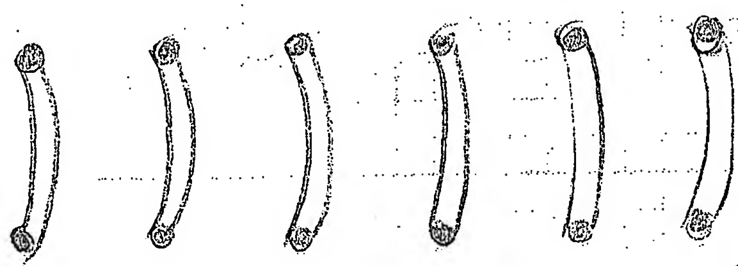


Fig 10B

Coil springs made from SCSMA can be used as Actuators (by heating), or superelastic elements when austenitic. 9% strain recovery and/or superelasticity offers significant enhancement over the 4% currently possible with SMA materials.

5/4/04

Probes / Pins

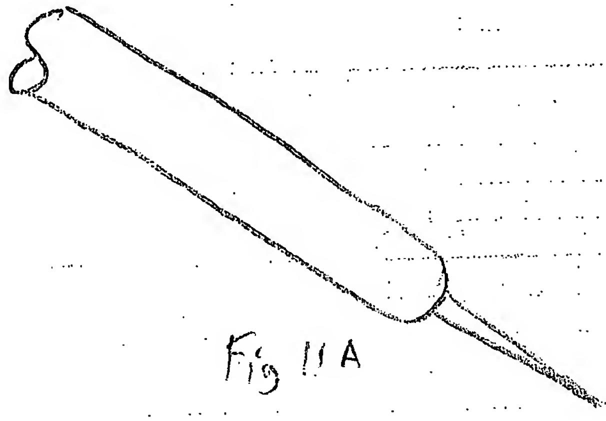


Fig 11A

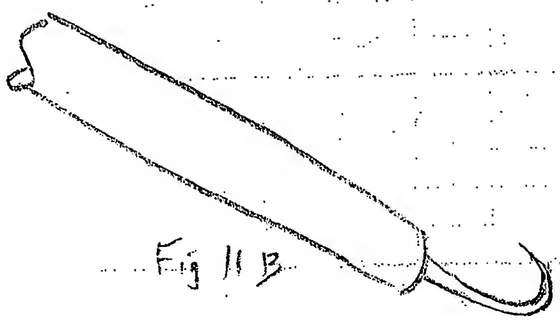


Fig 11B

The use of SCSMA allows for severe bending and inherent toughness resisting breakage. Application includes medical instruments, probes, and needles.